Advanced Lateral Crystal Growth of a-Si Thin Films by Double-Pulsed Irradiation of All Solid-State Lasers

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ABSTRACT

A compact annealing machine with all solid-state green lasers has been developed, which has the advantage of widely adjustable solidification rate through the delay time control of two long pulses (pulse width ~100ns). Advanced lateral crystal growth (ALCG) process has been proved by the double-pulsed all solid-state laser annealing. The laser beam has a line shape 0.1mm wide and 17mm long, and the beam profile on the short axis is quasi-Gaussian (FWHM 0.1mm). Scanning the line beam along the short axis at the 86% overlapping ratio, the lateral crystal growth area of width 14μm, parallel to the long axis, is sequentially formed at the pitch of 14μm towards the scanning direction. The advanced lateral growth mechanism is easily explained as follows: (1) At the first irradiation, twin seed lines of width 4μm, parallel to the long axis, generates at a boundary between a near-complete melting region and a complete melting region. (2) At the second irradiation of scanning step 14μm, the front seed line in the scanning direction grows symmetrically toward both sides. (3) At the third irradiation of scanning step 2x14μm, the seeds laterally grow until stopped by the growing of seeds on both sides. Finally the ALCG process by the scanning line-beam technique like the current ELA enables us to produce the laterally grown Si thin-films sequentially arranging the belt-shaped texture at the pitch of 14μm. The quality of the laterally grown Si films is quite well except for the projections generated by the bump of lateral growing seeds.

INTRODUCTION

In the roadmap of low-temperature poly-Si (LTPS) technologies [1], the high performance of thin-film transistors (TFTs) is to be demanded with the transition of TFT generations. High-quality LTPS films naturally are required for the high performance of TFTs. The current excimer laser annealing (ELA) method for crystallization, which is one of the key technologies in the LTPS-TFT process, is not able to apply in the next generation because of small Si grains of 0.5μm at maximum. In order to obtain high-quality poly-Si films, several crystallization methods by an excimer laser [2,3] and also by a reliable solid-state laser [4-6] were proposed, and are founded on controllable grain size and grain boundary position.

We propose a challenging crystallization method, appending the function of solidification rate control to the scanning line-beam technique like the current ELA. Our crystallization method, named advanced lateral crystal growth (ALCG), is based on double-pulsed laser irradiation controlling a delay time between two pulses of long duration, emitted from LD-pumped pulsed solid-state lasers. The all solid-state green lasers are expected to be of higher power in the near future. Here we describe a basic concept of the ALCG method and

discuss the quality of laterally grown Si thin-films.

CONCEPT OF ALCG

Advanced lateral crystal growth (ALCG) is the Si thin-film process of growing grains laterally by the scanning line-beam technique such as the present ELA and double-pulsed laser irradiation that is enabled to control the solidification rate. Controllable timing between long-duration pulse shots in the double-pulsed laser irradiation contributes to the generation of larger seeds and also to the more lateral growing of the seeds. The exact controlling of delay time and pulse energy in the double-pulsed laser irradiation holds the key to the ALCG process that has no need for a high performance stage, a high precision mask, and a complex optical system.

The ALCG process has two steps for lateral crystallization: to generate seeds at a steep slope of quasi-Gaussian profile on a short axis of a line beam, and to grow the seeds laterally toward both sides by the scanning of a line beam with overlapping until the growing seeds bump against each other. The temperature gradient due to the steep slope of the quasi-Gaussian beam shape produces continuously/ a partial-melting region, a near-complete melting (NCM) region, and a complete melting (CM) region with increasing temperature. On account of the multiplication effect of the temperature gradient and the double-pulsed laser irradiation, large seeds are generated at a boundary between the NCM region and the CM region. The first pulsed-laser shot forms twin-lines of seeds along a long axis of the line beam. It is expected from the simulation results shown in figure 1 that a double-pulse (DP) shot with a delay time is more effective for the generation of wide seeds than a single-pulse (SP) shot, because of its generating wider seeds more than two times. The second pulsed-laser shot at the next location scanned grows, preferentially and laterally, the front seeds in the scanning direction. The local temperature gradient due to a difference of optical absorption between the seeds and the fine texture becomes the driving force of lateral crystal growth. The frequent laser shots grow the seeds sequentially in the same manner until stopped by the growing of seeds on both sides. In the final stage the whole area scanned by the line-beam overlapped irradiation is periodically covered with the laterally grown, belt-shaped texture.

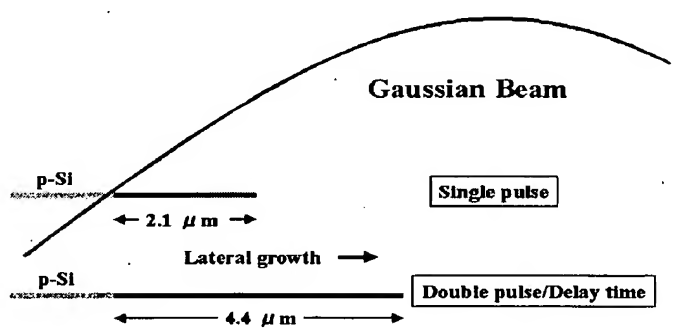

Fig.1. Simulation results of typical seeds generated by a single-pulse laser shot and a double-pulse laser shot.

EXPERIMENTAL DETAILS

Our double-pulsed laser annealing system has been reported in detail elsewhere [7]. Before

the development of the laser annealing system, the suitability of laser sources for the double-pulsed laser irradiation was confirmed with the simulation [8,9]: the influence of pulse-energy and delay-time fluctuations in grain growth and the potentiality for a single-pulse laser shot with long-duration. We roughly estimated the performance level that the two laser sources should need. The all solid-state green lasers adopted have the following performance: (i) long pulse duration of about 100ns; (ii) pulse energy stability less than 0.3 %; (iii) delay-time fluctuation less than 3ns. The high performance such as the all solid-state green lasers satisfies the level required as laser sources in the double-pulsed laser irradiation.

Amorphous Si samples of film thickness 50nm, having an underlayer of SiO_2 on a glass substrate, were dehydrogenated at first, and crystallized by the double-pulsed laser annealing system. The double-pulsed lasers have a line shape 0.1mm wide and 17mm long and the quasi-Gaussian profile with the full width at half maximum (0.1mm). The crystal of texture of seeds and laterally grown Si films was observed with an optical microscope and a field emission scanning electron microscope (FE-SEM). The quality, surface roughness and the degree of crystallization also was analyzed with an atomic force microscope (AFM) and Raman spectroscopy (RS) with a beam spot of diameter about 1μm. The FWHM of a Raman peak represents the ratio standardized by the Si(100) wafer.

Seed formation

Seeds for lateral crystal growth were formed by means of a single-pulse (SP) laser shot and a double-pulse (DP) laser shot. Figure 2 observed with the optical scope shows typical seed patterns formed by both SP and DP laser shots. Twin seed lines at a steep slope of quasi-Gaussian profile on a short axis of the line beam are formed parallel to the long axis. The width of seed lines is about 2μm for a SP laser shot and about 4μm for a DP laser shot. The values of line width come up to the expectation of the simulation as shown in Fig. 1.

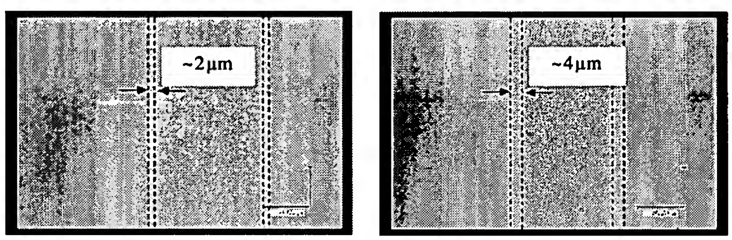

Fig.2. Optical scope images of typical seeds generated by a single-pulse laser shot and a double-pulse laser shot.

SEM images shown in figure 3 reveal which way the seeds are formed at a boundary between the NCM region and the CM region. The seeds are formed from the right side, the NCM region to the left side, the CM region. The seed formation against the temperature gradient starts from Si grains less than 1μm at the left end of the NCM region, and is blocked by Si grains generated in the CM region.

Figure 4 shows AFM images of a DP laser shot. The 2-D and 3-D images of AFM play an auxiliary role of the SEM images in Fig. 3. The left side of a seed line is the CM region made up of fine Si grains, and the right side is the NCM region of medium-size grains. The grain size

in the NCM region becomes greatest at the left end. The seeds are formed from the greatest grains in the NCM region against the temperature gradient. The CM region has the mean surface roughness (Ra) of 5.3nm and the NCM region the Ra value of 5.2nm. From a practical point of view, however, the maximum surface roughness slightly increases with the increase of grain size. The mean surface roughness (Ra=2.9nm) in the formation area of seeds is very smooth compared with the CM region and the NCM region.

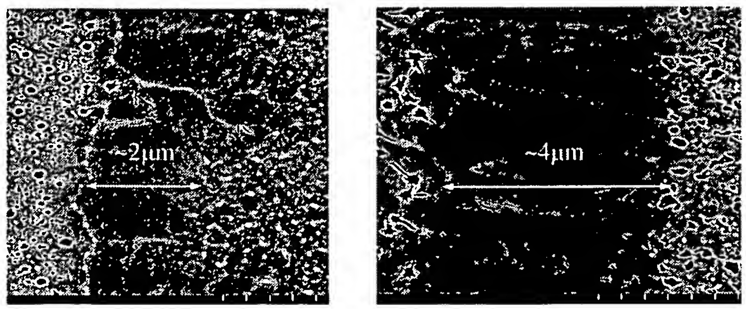

Fig.3. SEM images of typical seeds generated by a single-pulse and a double-pulse laser shot.

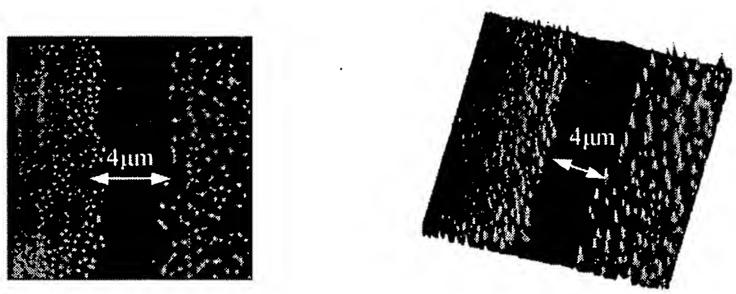

Fig.4. 2-D and 3-D AFM images ($15x15\mu m^2$) for a double-pulse laser shot under irradiation condition: E1/E2 ($800mJ/cm^2$, $700mJ/cm^2$), delay time (850ns), overlap ratio (-50%).

As shown in figure 5, the RS spectrum analyses of the seeds, formed by a DP laser shot, indicate as follows: (a) The seeds hold a low level of defects, deduced from the estimation of FWHM, near to the standard of the single Si crystal. (b) The crystal of texture of seeds looks homogeneous as the result of the small fluctuation of Raman peak shift and FWHM.

Advanced lateral crystal growth

Figure 6 shows the SEM images of Si films, grown laterally by the ALCG method. The whole scanning area, overlapped at the ratio 86% by the line beam irradiation of double-pulsed lasers, is covered with the belt-shaped texture grown laterally at a pitch of 14μm. The pitch is estimated from the line-beam width 0.1mm and the overlapping ratio 86%. When the lateral-growing seeds bump against each other, the lines of pitch 14μm are formed as the traces. There is a starting line of lateral growth in the center of the belt-shaped texture 14μm wide. The lateral grain growth is proved by the SEM images enlarged at the both sides of the starting line.

AFM images in figure 7 show clearly a starting line of lateral growth and the projections

generated by the bump of lateral growing seeds. On both sides of the starting line the lateral Si grain growth is symmetric and the twin seams of lateral growth exist on the way. The existence of seams in the lateral growing process gives evidence that the belt-shaped texture 14μm wide is formed by two-time double-pulsed laser shots after the generation of the seeds. The transition from the seeds to the symmetrical lateral growth, however, is still disputable. The projections are arranged with separation on the lines of pitch 14μm. The square area of 20μm x 20μm has the mean surface roughness of 3.6nm. From a practical point of view, the maximum surface roughness at the seams is 1.3 times as high as that in the most smooth lateral-growth area, the value Rmax at the starting line is 2.2 times, and the value Rmax at the projections is 5.1 times.

As shown in Fig.5, the RS spectrum analyses of Si thin-films, formed by the ALCG process, describe as follows: (a) The fluctuation of FWHM and Raman peak shift in the Si thin-films consisting of the smooth lateral-growth area and the projections is rather large than the fluctuation in the seeds. (b) The defect level of the smooth lateral-growth area is near to the single crystal, while the defect level at the projections generated by the bump of lateral growing seeds is higher than the defect levels of seeds and the smooth lateral-growth area.

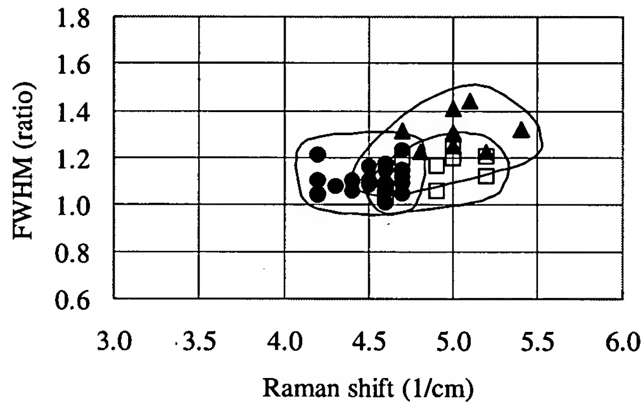

Fig.5. RS spectrum analyses of textures in Si thin-films: seeds (□), smooth lateral-growth area (●), projections (▲).

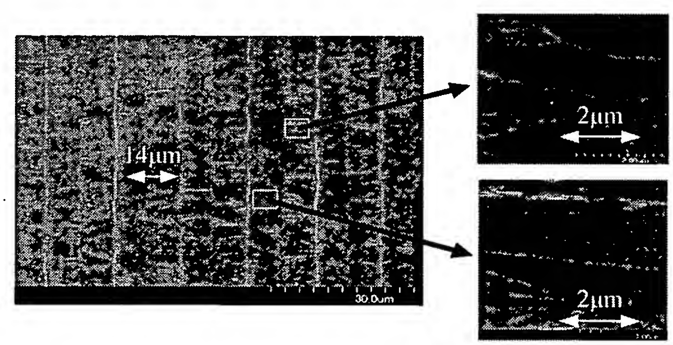

Fig.6. A SEM image and magnified images (x 9) of Si thin-films laterally grown by double-pulse irradiation: E1/E2 (800mJ/cm^2, 700mJ/cm^2), delay time (850ns), overlap ratio (86%).

SUMMARY

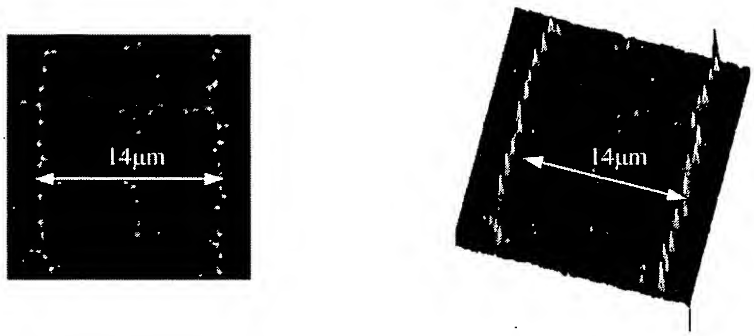

Fig.7. 2-D and 3-D AFM images ($20x20\mu m^2$) of Si thin-films laterally grown by double-pulse irradiation: E1/E2 ($800mJ/cm^2$, $700mJ/cm^2$), delay time (850ns), overlap ratio (86%).

The double-pulsed laser irradiation is very useful for growing Si grains laterally and largely, especially when all solid-state green lasers used as the reliable laser sources have the excellent pulse-energy stability and pulse-timing jitter, and laser pulses emitted have the long duration above 100ns. The high potentiality is given to a double-pulsed laser shot; high-quality Si grains above length 4μm are formed by the optimum irradiation. The excessive overlapping irradiation, however, becomes the quality of Si grains worse with increasing the ratio.

The advanced lateral crystal growth (ALCG) process by the scanning line-beam technique (line-beam size: 0.1mm x 17mm, overlap ratio: 86%) like the current ELA, enables us to produce the laterally grown Si thin-films sequentially arranging the belt-shaped texture at the pitch of 14μm. The quality of the laterally grown Si thin-films, evaluated by surface roughness and the degree of crystallization, is quite well except for the projections generated by the bump of lateral growing seeds. The maximum surface roughness of the projections is about 5 times as large as that of the standard smooth surface. It is essential for the ALCG process to improve the surface roughness due to the bump of lateral growing seeds, because the surface roughness leads to gate-insulator leakage current [10].

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